Measurement of the B_c^- Lifetime using $B_c^- \to J/\psi\ \pi^-$

The CDF Collaboration
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The lifetime of the B_c^- meson using the exclusive $B_c^- \to J/\psi\ \pi^-$ decay is measured with a data sample of 6.7 fb^{-1}. Several methods of extracting the lifetime are studied. These methods differ in the handling and modeling of the underlying background, selection criteria, and fitting technique. The relative agreement between these methods gives a strengthened confidence in the result.

The lifetime of the B_c^- is measured:

$$\tau(B_c^-) = (\ 0.452 \pm 0.048 \pm 0.027\ )\ \text{ps}$$
$$c\tau(B_c^-) = (\ 136 \pm 14 \pm 8\ )\ \mu\text{m}$$

I. INTRODUCTION

Theoretically, the lifetime of the B_c^- [1] meson is expected to be short as the B_c^- decay can proceed with either b quark or $\bar{c}$ anti-quark decaying in a spectator model or the B_c^- can decay through an annihilation process between the b and $\bar{c}$ quarks. Calculations exist using operator product expansion, potential models, QCD sum rules, and heavy quark effective theory. Most models agree that the lifetime should be *charm-like* and fall within in a predicted range of 0.4-0.7 ps.

CDF is the first experiment to observe the fully reconstructed $B_c^- \rightarrow J/\psi \ \pi^-$ decay mode and determine its mass. After 2.4 fb^{-1}, CDF published the following value [2]:

$$\text{Mass}(B_c^-) = (\ 6275.6 \pm 2.9 \pm 2.5 \ ) \ \text{MeV}/c^2$$

The measurement of the lifetime of the B_c^- has previously been performed by CDF in semileptonic analyses [3]. These measurements have a missing reconstructed neutrino and leptonic backgrounds. The current CDF measurement of the B_c^- lifetime using semileptonic decays (1 fb^{-1}) has found:

$$c\tau(B_c^-) = (142 \ ^{+16}_{-15} \pm 5 \ ) \ \mu\text{m} \ [\text{Combined } e \text{ and } \mu]$$

The Particle Data Group (PDG) average [4] includes a 2006 measurement of CDF (360 pb $^{-1}$) [5] in the electron channel and a 2009 semileptonic measurement by DØ (1.3 fb^{-1}) [6]:

$$c\tau(B_c^-) = (136 \pm 12 \ ) \ \mu\text{m} \ [\text{PDG}]$$

We present a new measurement of the lifetime of the B_c^- meson using the fully reconstructed $B_c^- \rightarrow J/\psi \ \pi^-$ final state which is only now possible as sufficient statistics allow for a well-behaved fit from which the lifetime can be extracted.

II. DATA SAMPLE & EVENT SELECTION

The CDF detector is described in detail in [7]. Approximately 6.7 fb^{-1} of data is used that has been collected using J$/\psi \rightarrow \mu^+ \ \mu^-$ triggers where two oppositely charged muons with an invariant mass in the J/ψ mass range are identified. To reconstruct $B_c^- \rightarrow J/\psi \ \pi^-$, three tracks required to each have at least 3 hits in the axial silicon system are subject to a combined vertex and J/ψ mass constraint. The "minimal selection" is made on kinematic quantities after the constrained fit including $P_T(B) > 5$ GeV/c and $P_T(\pi/K) > 1.7$ GeV/c.

Table I shows the "selection 1" and "selection 2" requirements. The selection 1 requirements have been optimized in terms of signal to noise while using selection variables that should not distort the decay time distribution. The selection 2 requirements are employed as a means to remove additional background in order to add additional candidates at lower decay time. Selection 2 has a decay time dependent function that describes an effective efficiency versus decay time. It was not known *a priori* whether the selection 1 or selection 2 requirements would result in a more precise determination of the B_c^- lifetime accounting for both statistical and systematic uncertainties since the decay time dependence of selection 2 needs to be accounted.

III. $B_C^- \rightarrow J/\psi \ \pi^-$ RECONSTRUCTION

Figure 1 shows the reconstructed $B_c^- \rightarrow J/\psi \ \pi^-$ mass distribution for both the selection 1 and selection 2 requirements. For both selections, a simple fit gives about 300 B_c^- events with the number of background events being about 8% less for selection 2.,

IV. MONTE CARLO

Monte Carlo, using a theoretically motivated B_c^- production spectrum [8], is used to derive a function that describes an effective efficiency of the selection criteria as a function of decay time.

The Monte Carlo is validated by comparing the distribution of all the selection criteria. Small disagreements between the data and Monte Carlo are evaluated in terms of causing systematic uncertainties in the extracted lifetime.

Selection variable	selection 1	selection 2
$P_T(\pi)$	> 2.0 GeV/c	> 2.0 GeV/c
$P_T(J/\psi\ \pi)$	> 6.5 GeV/c	> 6.5 GeV/c
$Prob(\chi^2_{\text{CTVMFT}})$	$> 0.01\%$	$> 0.1\%$
$\sigma[M(J/\psi\pi)]$	-	< 40 MeV/c^2
$\sigma[c\tau(J/\psi\ \pi)]$	$< 100\ \mu$m	$< Max[35, 65 - 3 \times P_T(\text{B})\text{GeV}/c]\ \mu$m
2D Pointing angle, β_T	-	< 0.2 radians
$\|ip_{\text{signif}}(J/\psi\pi\ \text{wrt p.v.})\|$	$< 2.0\ \sigma$	$< 2.0\ \sigma$
Track isolation (cone=0.7)	< 0.6	< 0.6
$c\tau_{\text{MIN}}(J/\psi\ \pi)$	$> 120\ \mu$m	$> 80\ \mu$m

TABLE I: Selection variables for $B_c^- \to J/\psi\ \pi^-$ where $Prob(\chi^2)$ is the probability of the χ^2 from the constrained fit, $\sigma(M)/\sigma(c\tau)$ is the uncertainty in the mass/decay time after a full propagation of covariance matrix errors, β_T is the 2D angle between the $J/\psi\ \pi^-$ momentum vector and the vector from the primary vertex (p.v.) and the secondary vertex (s.v.), impact parameter (ip) significance is with respect to the primary vertexto the s.v., track isolation is the fraction of P_T carried by the $J/\psi\ \pi^-$ candidate relative to all other charged tracks with $P_T > 0.4$ MeV/c in a $\Delta\phi\ \Delta\eta$ cone of 0.7 around the candidate flight direction, and $c\tau_{\text{MIN}}$ is the minimum decay time used in the fit.

A. Effective efficiency vs decay time

Selection 1 is studied using sideband-subtracted $B^- \to J/\psi\ K^-$ data to verify that the selection is independent of decay time. Figure 2 (top) shows the effective efficiency versus decay for selection 1 sideband-subtracted $B^- \to J/\psi\ K^-$ decays relative to the "minimal selection". Note that no evidence for any decay time dependence is observed. Selection 2 is also studied using Monte Carlo and the sideband-subtracted $B^- \to J/\psi\ K^-$ data in terms of the effective efficiency versus decay time. Figure 2 (bottom) shows the effective signal efficiency versus decay time for selection 2 sideband-subtracted $B^- \to J/\psi\ K^-$ decays relative to the "minimal selection." Also shown is the Monte Carlo prediction (independently normalized) superimposed showing very good agreement and providing confidence that we can employ an effective efficiency for $B_c^- \to J/\psi\ \pi^-$ decays as well. Finally, Fig. 2 (bottom dashed) shows the expected effective efficiency versus decay time for $B_c^- \to J/\psi\ \pi^-$ decays.

V. LIFETIME OF THE B_C^- MESON

A combined mass and lifetime unbinned likelihood fit to the data is employed to extract the B_c^- lifetime. The fit includes parametrizations that describe the background both in mass and decay time. For the signal, the mass is expected to be nearly Gaussian described by its width and also have a decay time distribution that is expected to be an exponential convoluted with a resolution. For selection 2, the probability distribution function (PDF) of the signal includes the parametrization of the effective efficiency versus decay time due to the selection requirements. Details of the default fitting techniques are different for selections 1 and 2. Studies have been performed that validate both methods in terms of being able to extract unbiased lifetimes and returning an appropriate statistical uncertainty.

A. Fitting Technique

1. Selection 1

For selection 1, the strategy is to determine parameters that describe the background using a sideband region. Then, in the signal region, a combined fit is performed where the background parameters are fixed and only the signal parameters and the relative fractions of signal and background float. Figure 3 shows the fit from the signal region such that of the 2319 entries, $13.3 \pm 1.7\%$ ($308 \pm 39\ B_c^-$ candidates) are expected to be signal with mass 6273.0 ± 2.7 GeV/c^2 (consistent with [2]). The fitted lifetime is $135 \pm 16\ \mu$m which will be used to compare to the results from selection 2.

2. Selection 2

For selection 2, the strategy is to begin first by fitting only sideband to estimate the background parameters and then by fitting both background and signal events over the B_c^- signal range of interest. The choice of the parametrization of the background includes a linear mass model and a decay time distribution described by 3 exponentials where the third exponential helps parametrize the small number of background events at long lifetime. The parameters are first determined for a lower and upper sideband region from 6.16 to 6.60 GeV/c^2 that excludes a signal range of 6.21 to 6.33 GeV/c^2. Then an unbinned likelihood function fit to the data over the signal range is made where both the signal parameters (Guassian mass and exponential lifetime convoluted with the selection 2 effective efficiency versus decay time) and background parameters are fit. The fit is subject to Gaussian constraints imposed upon the background parameters from the sideband fit and Gaussian constraints imposed upon the determination of the effective efficiency versus decay time from the fitted Monte Carlo prediction. Figure 4 shows the projections of the fitted mass and lifetime distributions for signal and background overlaid with the data distributions. The fitted B_c^- mass is 6274.6± 2.9 MeV/c^2 in good agreement with [2]. The fitted B_c^- lifetime is 136 ± 14 μm.

VI. SYSTEMATIC UNCERTAINTIES

We consider several sources of systematic uncertainty in the lifetime determination. CDF has a long history of measuring B hadron lifetimes and the data from Run II is well-calibrated. The largest source of systematic uncertainty comes from the unique aspects of $B_c^- \to J/\psi \ \pi^-$ namely the relatively small number of observed events, relatively low signal to background, and the short lifetime compared with the other B hadrons. These unique aspects interplay with the uncertainties in calibration, PDF modeling of the signal and background, and variations in the fitting method.

A. Calibration

The CDF 2 detector is well-calibrated and reliable lifetime measurements have been made throughout the course of Run II. There are small possible residual detector misalignments that have been evaluated and give an uncertainty of 0.007 ps (2 μm) [9] which we take as a calibration systematic.

B. Modeling of the Signal

The modeling of the signal probability distribution function has some uncertainties that have been evaluated to quantify the resulting uncertainty on the lifetime determination. The expected mass model for the signal is well understood and gives rise to very small uncertainties in the lifetime extraction. A study of varying the width of the expected mass resolution results in a 2 μm variation in the fitted lifetime which we take as a systematic for selection 1. As the width is floating for selection 2, we assign a 1 μm systematic which comes from studying whether the inclusion or lack of inclusion of a possible Cabibbo-suppressed component might influence the final result. For the signal decay time model, we expect no systematic biases for selection 1. For selection 2, there are uncertainties as the model for the signal includes the effective efficiency correction as a function of decay time. Varying the efficiency curve determined by the Monte Carlo by shifting it by ± 20 μm, gives a 3 μm uncertainty.

C. Modeling of the Background

For the uncertainty in the mass model of the background for selection 1, we assign a 3 μm systematic to account for differences obtained if a bi-linear parameterization is used with a break at the center of the B_c^- peak. When studied with selection 2 requirements, this alternative model shows a 5 μm effect.

For the uncertainty in the decay time model for selection 1, we notice up to an 8 μm shift when one of the background parameters are fixed to a 1 σ variation. For selection 2, we assign 4 μm systematic based upon a study that compared an alternative background model that used two exponentials plus a linear function in order to model the sideband decay time distribution.

Both fitting methods have been simulated and typically show less than 1 μm of possible bias under simulations of various artifically inputted decay times and signal fractions. We assign 1 μm as a systematic. We also have performed a number of other cross-checks and tests for which no strong statistically significant variation is observed; however,

we assign 3 μm as a systematic uncertainty to account for the possibility that some of the variation is systematic in nature.

The systematic uncertainties associated with both selection 1 and selection 2 are summarized in Table II showing that indeed the statistical uncertainty dominates the overall uncertainty.

Systematic	Selection 1	Selection 2
Calibration	2	2
Signal Mass Model	2	1
Signal Decay Time Model	-	3
Background Mass Model	3	5
Background Decay Time Model	8	4
Fitting Method	1	1
Other Tests	3	3
Total	10	8

TABLE II: Summary of systematics.

VII.   RESULTS

As the selection 2 methodology returns the overall lowest uncertainty, we take it as the central value. We note the good agreement with the selection 1 fitted value. Using the exclusive $B_c^- \to J/\psi \, \pi^-$ decay, we measure the lifetime of the B_c^-:

$$\tau(B_c^-) = (\ 0.452 \pm 0.048 \pm 0.027\ )\ \text{ps}$$
$$c\tau(B_c^-) = (\ 136 \pm 14 \pm 8\ )\ \mu\text{m}$$

We have used several methods to measure this quantity and they agree giving additional confidence in the result. We note that our chosen central value comes from a selection that distorts the decay time distribution. However, this distortion is modeled by the Monte Carlo and uncertainties in correcting for this distortion are small compared with the statistical uncertainty of the measurement.

[1] A particular charge state implies the conjugate unless explicitly stated.
[2] T. Aaltonen *et al.* [CDF Collaboration], "Observation of the Decay $B_c^\pm \to J/\psi\pi^\pm$ and Measurement of the $B_c^\pm$ Mass," Phys. Rev. Lett. **100**, 182002 (2008) [arXiv:0712.1506 [hep-ex]].
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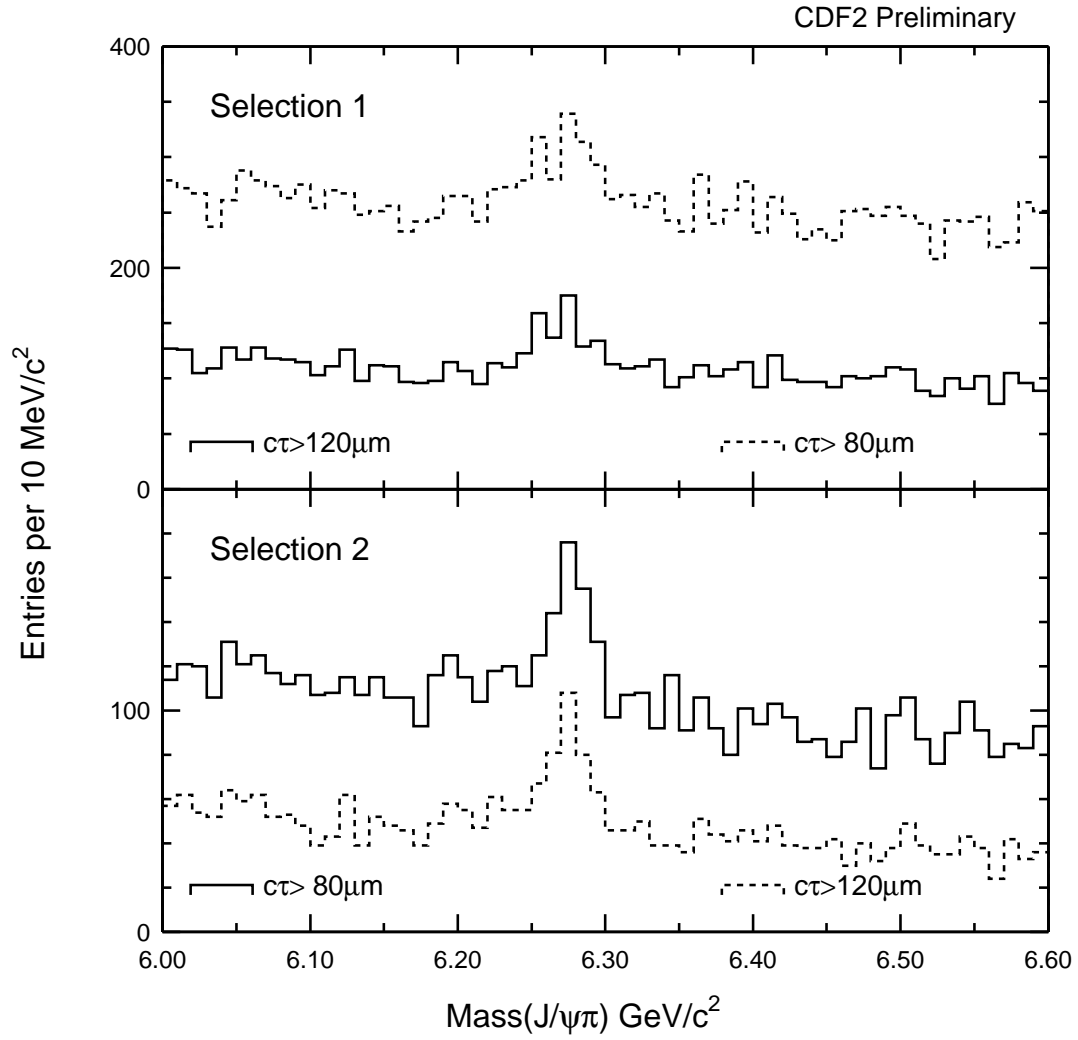
FIG. 1: $J/\psi\ \pi$ mass distributions using the (a) selection 1 and (b) selection 2 selection as described in the text.
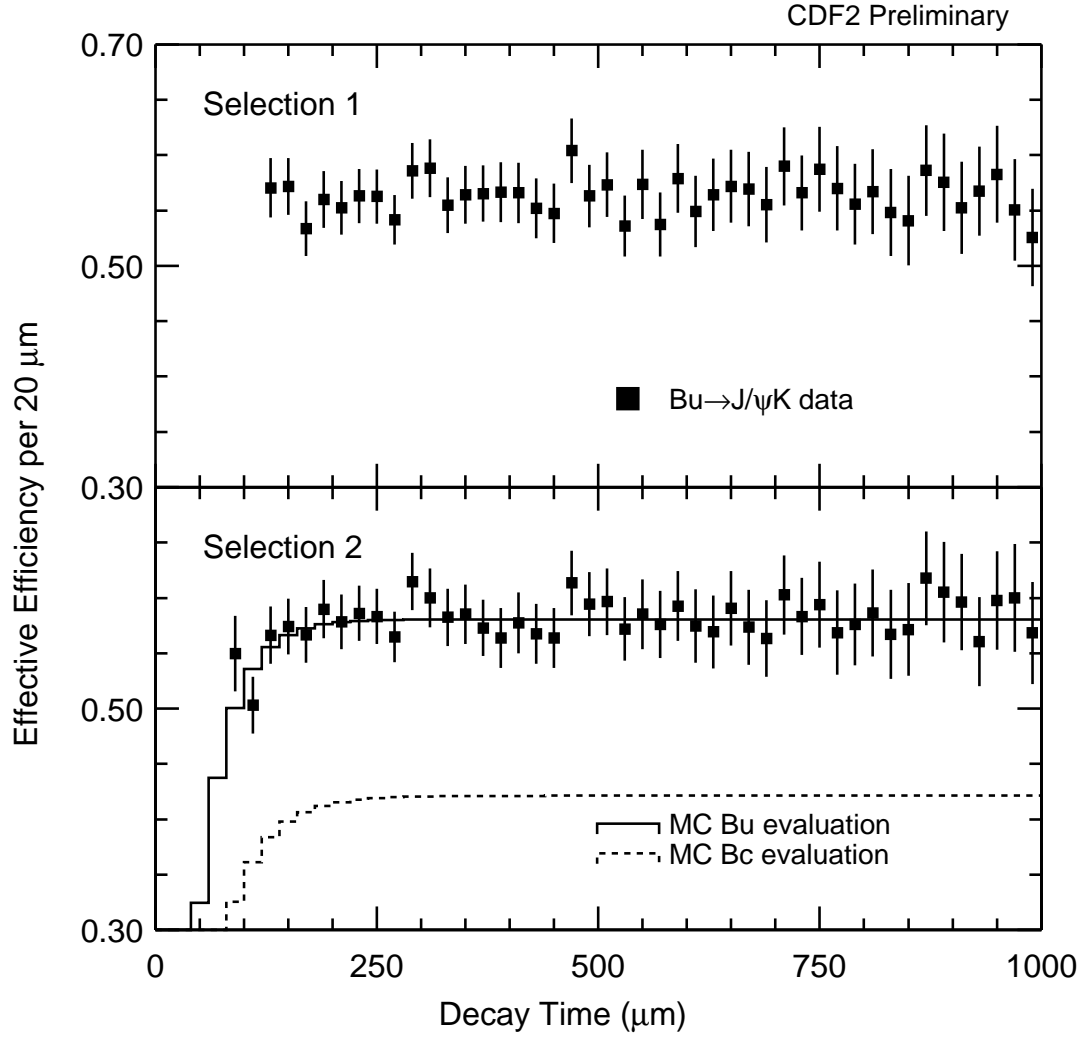
FIG. 2: Sideband-subtracted $J/\psi\ K$ decay time distributions relative to the minimal selection for (top) selection 1 and (bottom) selection 2. For selection 2, a superimposed function derived from Monte Carlo is shown (solid). Also shown, is the Monte Carlo derived efficiency for $B_c^- \rightarrow J/\psi\ \pi^-$ (dashed).
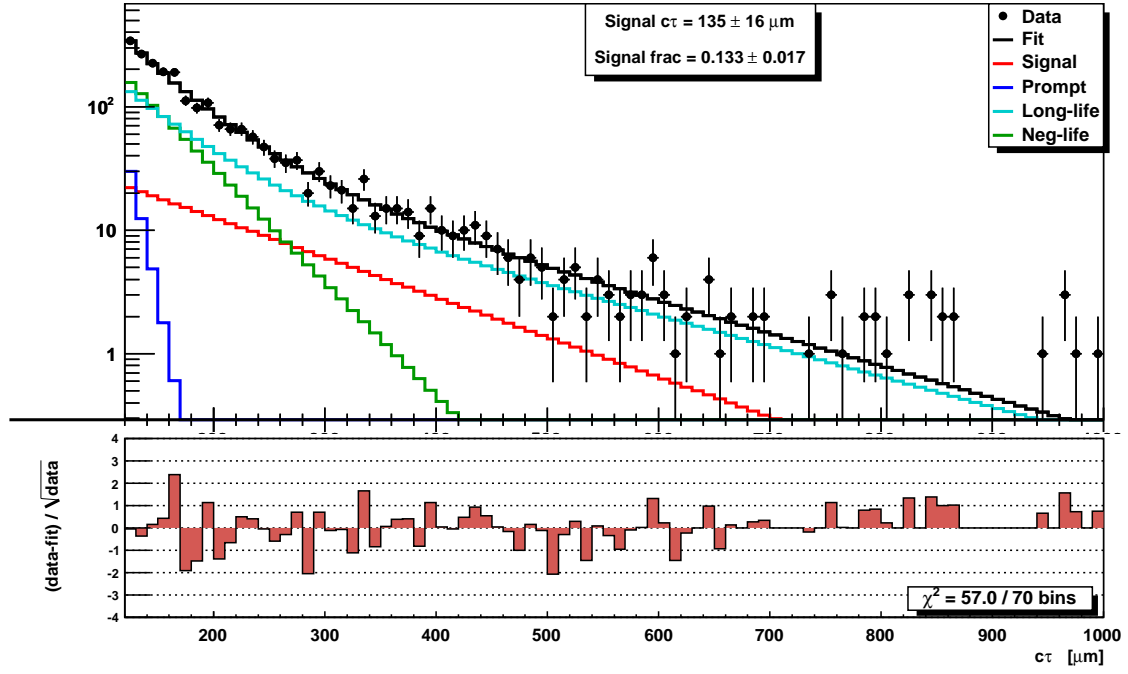
FIG. 3: Selection 1 $B_c^- \to J/\psi \, \pi^-$ decay time distribution after the combined mass and lifetime fit showing the various components of the fit.
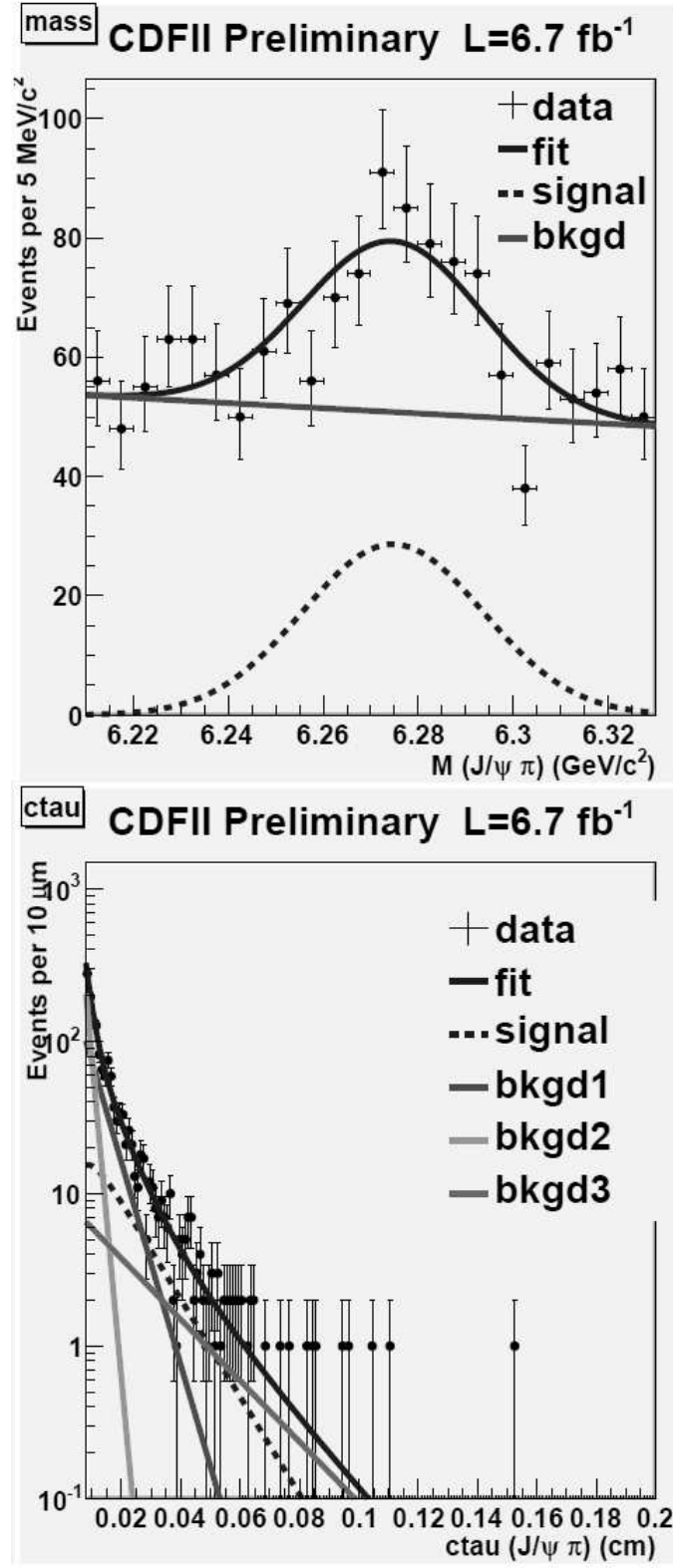
FIG. 4: Selection 2 $B_c^- \to J/\psi \, \pi^-$ distributions in mass and decay time superimposed with the fit showing separate signal and background components.